ILC KLYSTRON DESIGN OPTIONS

AND

KLYSTRON MANUFACTURING

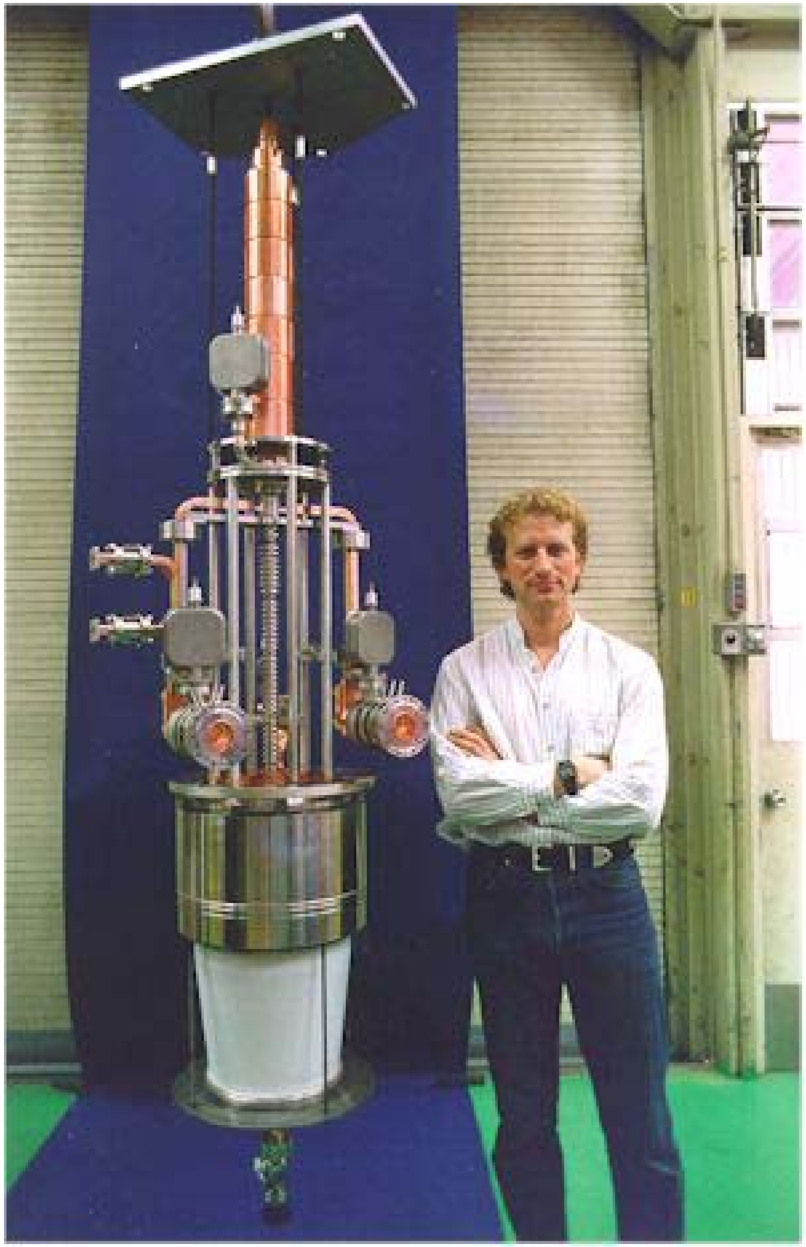
G. CARYOTAKIS

SNOWMASS 2005

Since the first experimental electron-positron collider was built (the CBX experiment at Stanford in 1962), every collider constructed thereafter has required the parallel development of a high power klystron.

Beginning with the working SPEAR ring collider, a 175 kW CW UHF klystron was developed at SLAC in the early 70's, and later redesigned for 500 kW CW for the PEP I machine. The final design was widely imitated by the European tube industry, which supplied similar klystrons for LEP and Tristan. After experimenting with substandard Philips and EEV 1-MW klystrons for PEP II, SLAC has settled on a SLAC-manufactured 1.25 MW CW tube which has proven both its reliability and necessary linearity.

In linear colliders, the pulsed klystrons required have presented more challenging design problems because of the combination of high average and peak power at the output circuit. We can estimate the electro-mechanical stresses there (both rf breakdown and intra-pulse heating) by calculating the energy in a single rf pulse (and normalize to S-band by the inverse of the square of the frequency to account for the output cavity surface). This "difficulty factor" for the first linear collider klystrons (the SLAC SLC 65-MW 5045) is 250. In comparison, the 150-MW klystron developed at SLAC for the DESY short-lived "warm" collider had a factor of 450, while the factor for the SLAC 75-MW PPM NLC klystrons, (normalized by the square of the frequency), is 1800.



The NLC 75-MW PPM klystron

In the ILC "cold" machine, the lower frequency reduces output circuit stress, but the 1000x longer pulse acts in the opposite direction. The "difficulty factor", normalized to S band, is approximately 7,000.
Actually, the stresses due to the long pulse are difficult to estimate and the above comparisons are probably overstated. Nevertheless, a 10-MW, 1.5 ms klystron is a fairly daunting microwave tube to design and manufacture, particularly if the efficiency target is 70.

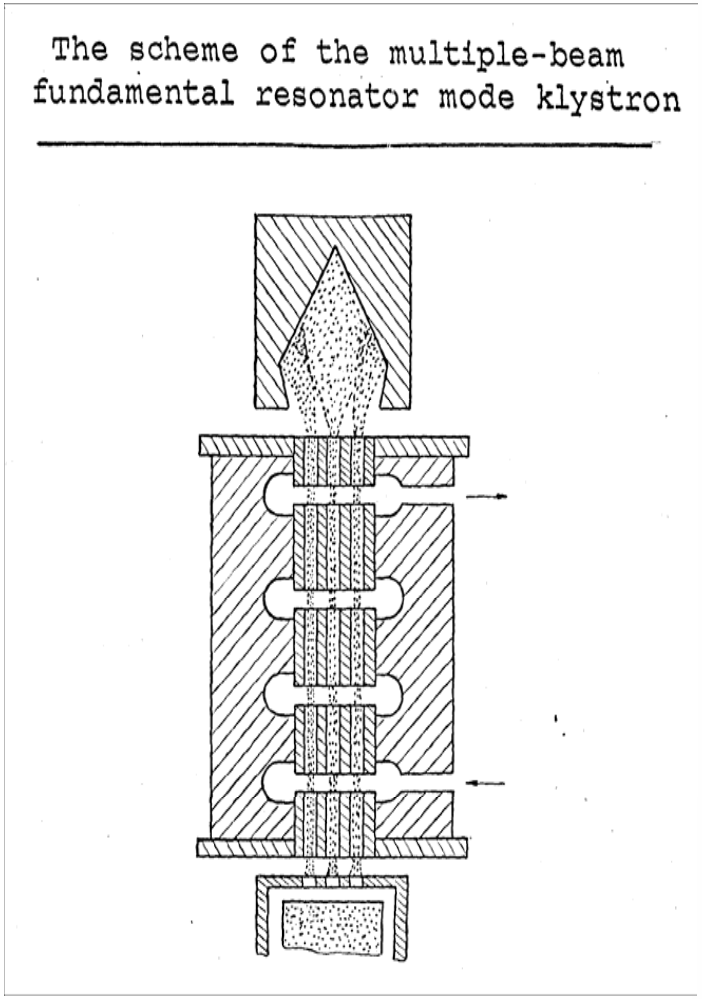
This was the efficiency specification to Thales for the TESLA klystrons. It (and modulator requirements) led directly to the multiple beam klystron design (MBK) since in an MBK individual beam currents (and space charge) are low, permitting tighter rf bunches and better efficiency.

MBKs have been used extensively in Russia. The Russian designs are characterized by densely packed beams, sometimes 50 or more, in individual drift tubes, at the center of common cavities. This allows high beam currents to be used, without the potential depression that that would occur in a single, large diameter beam.

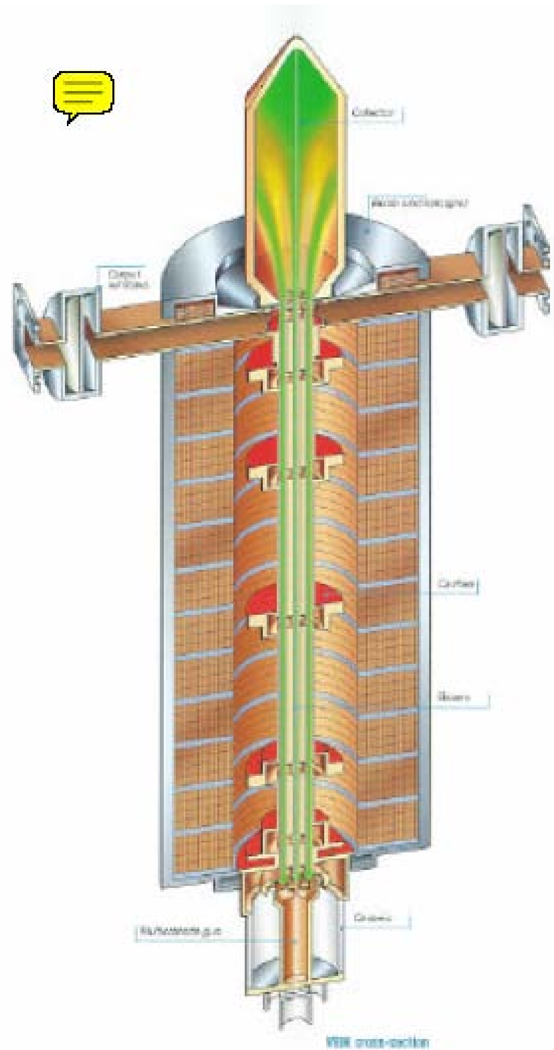
However, this design has the disadvantage that the tight beam spacing does not leave sufficient space at the electron gun for a focus electrode. As a consequence, such beams are not designed with sufficient area convergence and, in some cases, cathodes may become current limited.

The Thales MBK may have this problem. The current density in its 7 cathodes is estimated to be over 4 A/cm^2. For the 1.5 millisecond pulse length, this may require a cathode temperature of over 1100 ^{0}C. The resulting barium evaporation rate may shorten tube life by creating anode deposits that trigger gun arcs. This is consistent with some of the reports from DESY on tests of the Thales MBK there.

If this diagnosis is accurate, the solution can only be a complete redesign of the tube, or a better cathode, operating at a lower temperature. There is ongoing research in China on a mixed tungsten/scandium matrix dispenser cathode, which we are monitoring at SLAC. We have received several of these presumed low-temperature Chinese cathodes and will be life-testing them soon.



Conceptual Russian MBK design

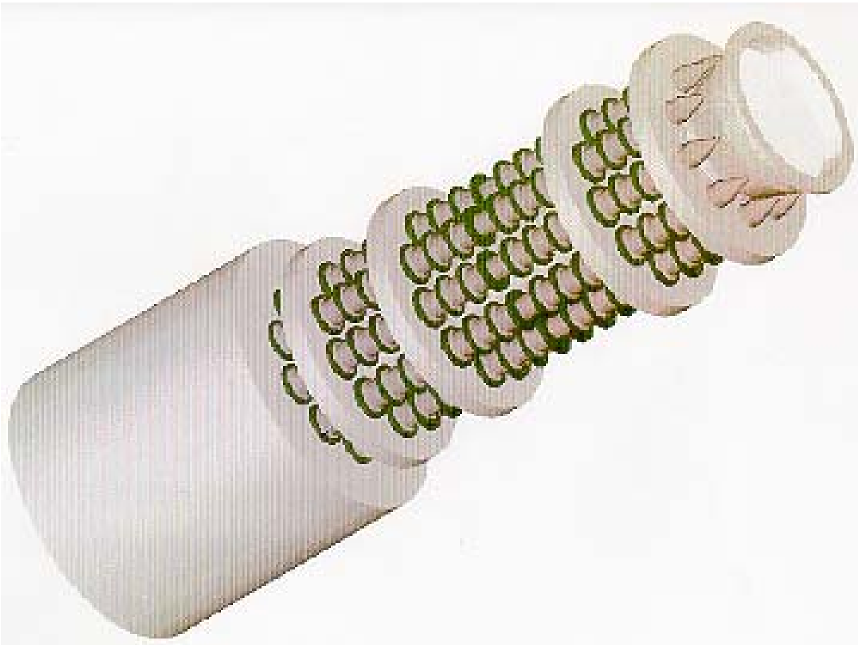


Thales TESLA 7-beam design

The CPI MBK is of a different design. Its origins can actually be traced to SLAC, where an L-Band MBK was designed on a “work for others” grant to produce 1 Gigawatt microsecond pulses. In this design the beams were placed on a much larger “bolt circle” (the 4 cavities were actually rings), allowing room for focus electrodes and hence a sufficient beam convergence. In this design, which followed at the heels of the successful 50-MW PPM NLC klystron, the 10 beams were also PPM focused.

Ed Wright, the project engineer on the SLAC study eventually migrated to CPI and supervised the design of the CPI TESLA MBK. Like the SLAC tube, the CPI MBK has common input and output cavities to all beams but intermediate (gain and buncher) cavities are individual to each beam. (I understand that in the Toshiba MBK all cavities are common rings, just as in the SLAC paper MBK)

The net result is that, since this design allows for beam convergence, the cathode current in the CPI MBK is only about 2 A/cm^2. It is estimated that the CPI cathodes can be cooler by at least 50 ^0C than the Thales tube. This can triple the useful life of the tube.

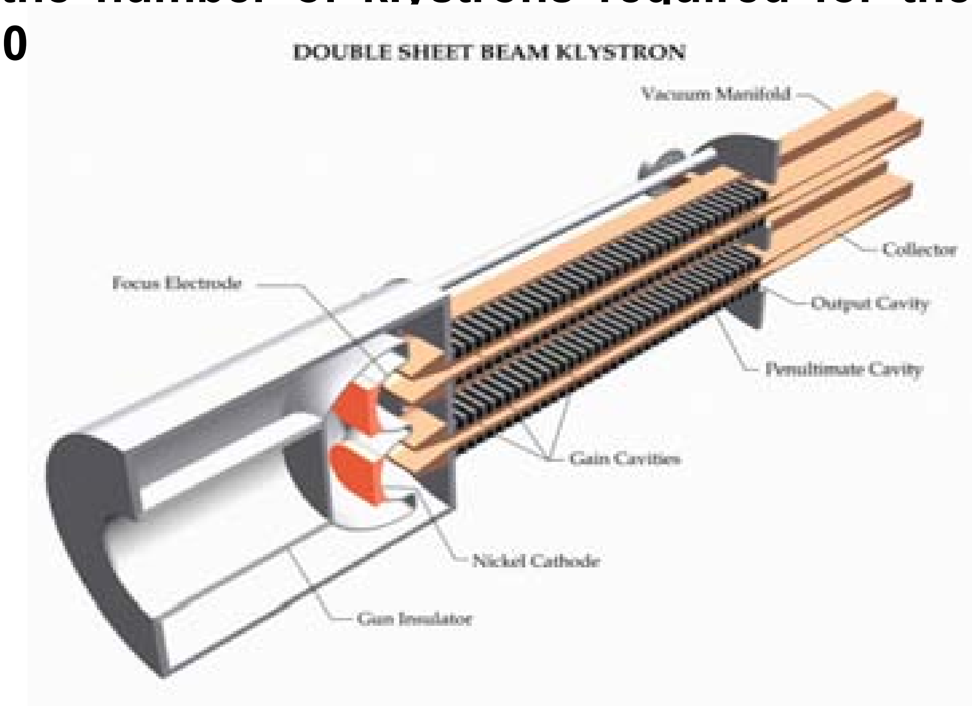


The SLAC "paper" 1-Gigawatt
10-beam PPM MBK (1996)

The CPI 6-beam MBK

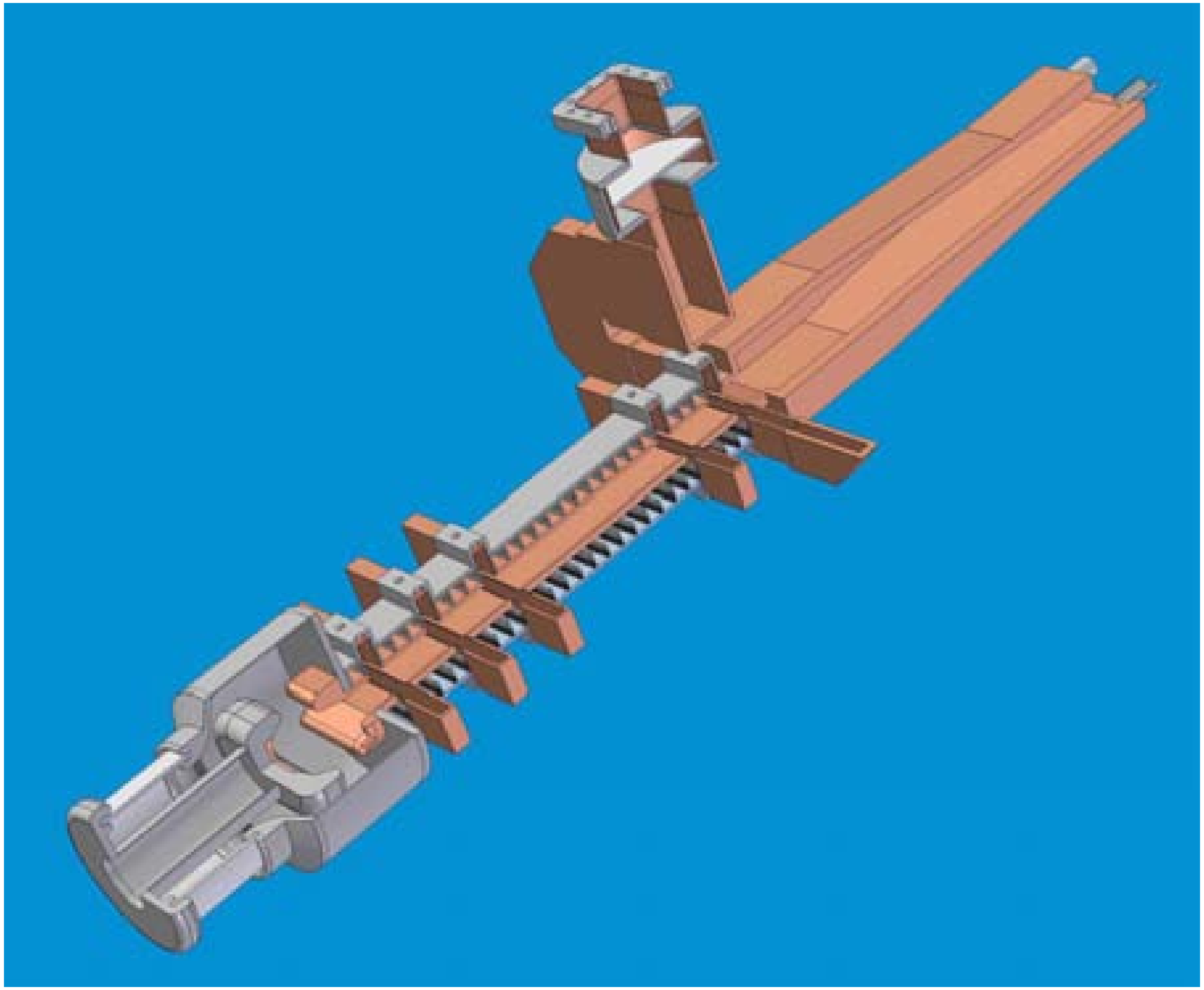
(Solenoid-focused)

Despite the relative success we had at SLAC in building prototypes of the NLC PPM klystrons, some of us had serious doubts whether these klystrons could be economically mass-produced in the quantities required. A drastically different design, a “sheet beam klystron” (SBK) was considered and pursued (on paper) until the NLC lost to TESLA. In addition to the promise of significantly lower manufacturing cost, the SBK offered the potential of building a 150-MW “double”SBK which would cut the number of klystrons required for the NLC from 4000 to 2000



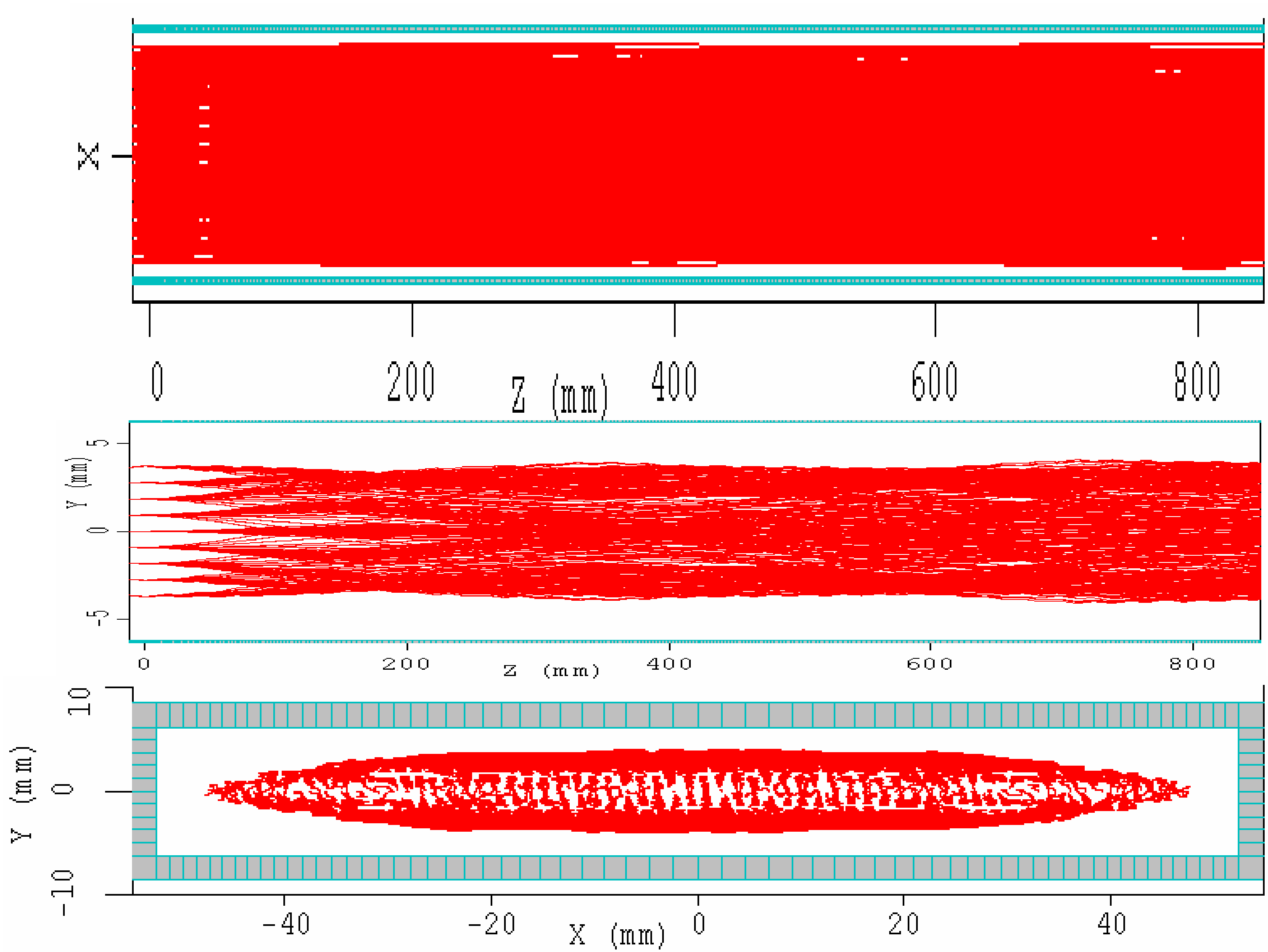
After the “cold” ILC was selected we began a design of an L-band SBK, “plug compatible” (same power, voltage and current) with the MBKs purchased by DESY. It was an attractive alternative because, unlike the NLC X-band SBK, the lower frequency and current of this ILC candidate permitted to design for a beam tunnel that is completely cut off for both TM and TE modes. In higher frequency SBKs this not possible, leaving open the possibility of TE modes becoming excited by beam or other irregularities. If these modes can propagate in the drift tube they could provide feedback paths for self-oscillations. This is not possible in this L-band design. The drift tube, which is relatively much smaller because of the low current and frequency, is completely cut off to both TE and TM waveguide modes.

The other issue encountered in SBK design, beam transport, is not present at L-band, for the same reasons. The figure below shows the periodically focused beam traversing the entire length of the tube without interception or breakup. The peak focusing field is only 400 gauss. The elliptical cross-section beam is produced by a special electron gun designed at SLAC

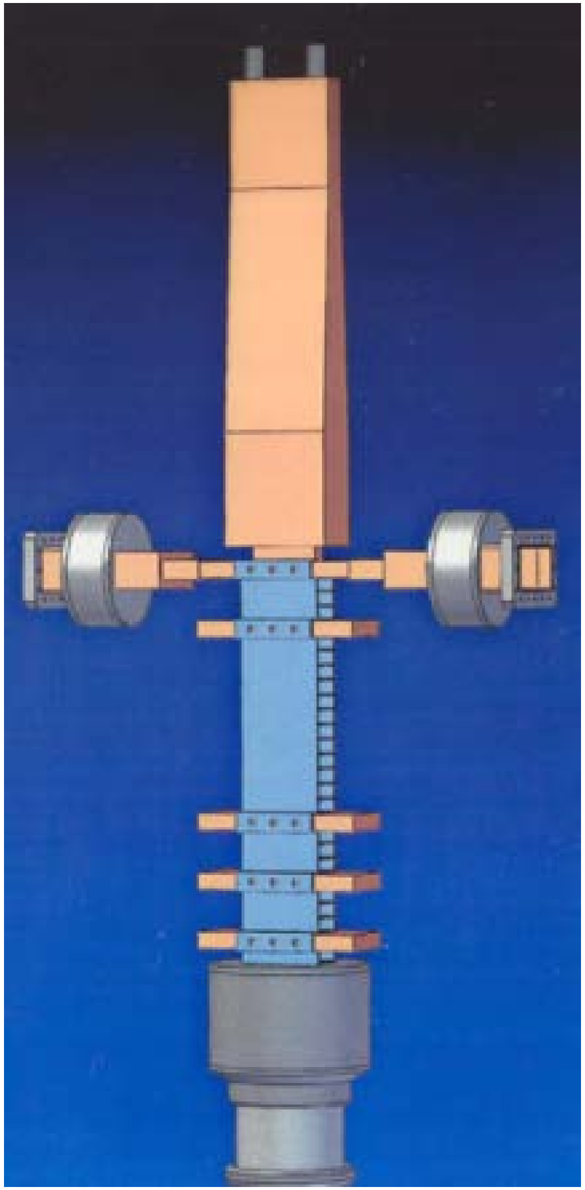


The proposed SLAC ILC SBK

(Shown here with a single window)



Top (width), side (height) and cross section of the PPM-focused ILC MBK beam. The MAGIC simulation was performed over the entire 85-cm length of the tube and required 90 computer hours



Comparing the CPI MBK to the SLAC SBK. The SBK is less costly because of fewer parts

Recently, work on the ILC SBK at SLAC was suspended because of budget difficulties. In what follows, we will argue that this was a bad decision and should be reversed.

First, let us examine the relative costs of the CPI MBK (the only relevant existing klystron today), and the (proposed) SLAC SBK. The CPI price for their prototype MBK sold to DESY was approximately $800,000, with magnet. It is estimated that the price of the next 10 tubes and magnets would be $550,000 each. We will perform a "learning curve" calculation. From 10 to 640 tubes (a convenient number) there are n=6 "doublings". Using a time-tested learning factor of 0.85 we obtain for the total price of 640 MBKs:

$$\text{Price} = \$550{,}000 \times 640 \times (0.85)^6 \approx \$133 \text{ million}$$

Or, about $208,000 in quantity 640.

The SLAC SBK is estimated at approximately ½ the cost because of its relative size and considerably fewer machined parts.

These tubes can be manufactured at SLAC. Alternatively, drawings can be provided to industry if after the SBK is developed, they choose to produce it.

Obviously, we cannot predict commercial prices for a non-existent tube. However if we use the expected CPI price and the estimated cost for a SLAC-manufactured SBK, the difference is $66.5 million in 2013 dollars, a present value of approximately $50 million (7 years, 4% cost of money)

The cost of a SLAC program to develop an ILC prototype has been estimated to require 2 years and $2 million. We are therefore weighing the pros and cons of spending $2 million now in order to save $50 million in building the ILC

Granted, no one has yet built or tested an SBK to date. (Mostly because it is a difficult 3-D simulation to perform). However, we have simulating SBKs for 5 years at 1.3, 11.4, and 30 GHz (CLIC), and we are about to test a 100-kW SBK at 95 GHz.

The choice to develop, or not, an ILC SBK would appear to be an easy decision to make, if one were convinced of the following:

- That the ILC fate will depend on its cost, and that all costs will be scrupulously examined.
- That SLAC employs a competent klystron design group.

Conclusions

An SBK device is a viable alternative for the main rf power source of the ILC.

The cost of an SBK should be about half that of an equivalent MBK.

Funding for developing an ILC SBK should be restored.

Machine shop

Parts inspection (QA)

Clean room assembly

Furnace room (brazing)

Electron gun vacuum firing and processing

Klystron baking and exhaust (6 stations)

Part of the test high bay area (13 high voltage test stations)

The other half of the high bay test floor. Two 10-ton cranes overhead)